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NASA SP-21

26p  
N63-11511  
code 1

SESSION O

**Power for Spacecraft**

**Chairman, NEWELL D. SANDERS**



## 46. Power for Spacecraft

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### INTRODUCTION

NEWELL D. SANDERS. The electric-power requirements for spacecraft may be classed in two categories, power for auxiliary systems and power for electric propulsion. Examples of the first category are the requirements established by life support, attitude and course control, scientific measurements, and communications systems. These requirements for auxiliary power systems face us today. The demands of electric propulsion are in the future but because of the great size and stringent requirements on these systems, their development will be difficult and lengthy.

Sources of energy that are available to spacecraft are chemical sources, the sun, and nuclear energy from reactors or isotopes. Energy from these sources may be converted to useful electric power by devices or techniques, such as fuel cells, thermodynamic engines, photovoltaic effect, thermionics, and thermoelectricity.

Certain aspects of the interrelation of power requirements, energy sources, and conversion techniques are discussed in this paper.

### MISSIONS ILLUSTRATING REQUIREMENTS

DANIEL T. BERNATOWICZ. Up to now the electric-power systems used in NASA space missions have differed little in basic character. The power required on board most satellites and space probes launched to date has been less than a few tens of watts. This power has been supplied by solar cells with batteries for peak

power demands and for storage for dark periods. For future missions, the diversity among the power systems will be more striking than the similarity. One of the principal factors influencing this diversity is the wide range of power level required. Figure 46-1 shows anticipated maximum requirements for nonpropulsive and propulsive electric power plotted against calendar year. The nonpropulsive power needs grow about a thousandfold in 10 years, from less than 100 watts for early satellites to several hundred kilowatts in the early 1970's. Power requirements for electric propulsion start at about 60 kilowatts for unmanned probes to the planets and extend well above 1 megawatt for manned interplanetary missions.

A few examples will illustrate the need for this wide spectrum of power. Typical of the small solar-powered satellites is Explorer XII

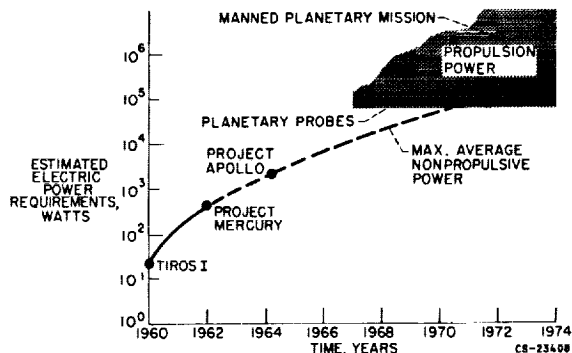


FIGURE 46-1.—Anticipated nonpropulsive and propulsive space-power requirements.

(fig. 46-2), which was launched in August 1961 to study the zones of energetic particles around the Earth. Solar cells mounted on the four panels furnished about 20 watts of power.

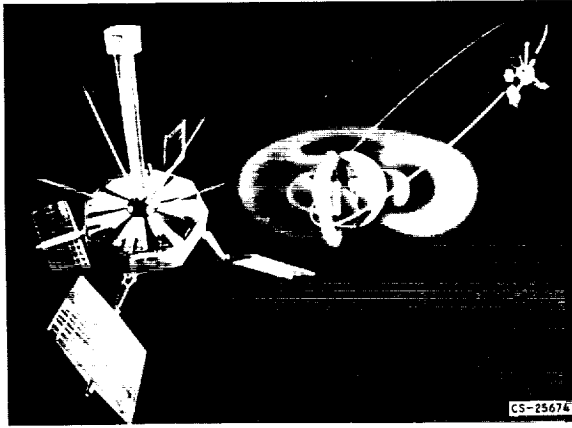


FIGURE 46-2.—Explorer XII.

A mission requiring a few kilowatts of power is Apollo, the objective of which is the landing of men on the Moon in this decade (fig. 46-3). The main power supply will be hydrogen-oxygen fuel cells providing an average power of about 2 kilowatts for 2 weeks. Two of the three astronauts will land on the Moon in a lunar excursion module. The power system for the landing module has not been selected, but it may be a fuel cell or a chemically fueled engine. It must supply several hundred watts for a period of up to 1 week.

An application requiring 20 kilowatts or more of power is the orbiting space platform,



FIGURE 46-3.—Apollo vehicle.

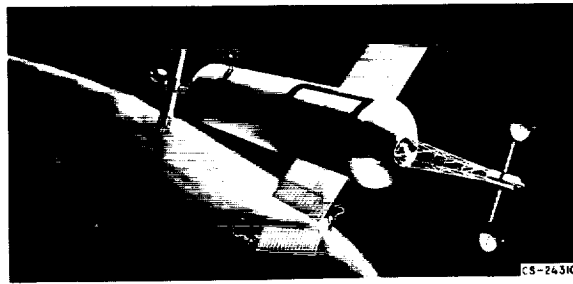


FIGURE 46-4.—Orbiting space laboratory. Estimated power requirement, 60 kilowatts; booster, Saturn C-5; gross weight, 200,000 pounds.

one concept of which is shown in figure 46-4. Because the useful life will have to be at least 1 year, a nuclear or solar power system will be selected. The figure shows men assembling a radiator for rejecting the waste heat from a nuclear powerplant.

When exploration of the distant parts of the solar system is undertaken, even unmanned vehicles may require huge powers. Figure 46-5

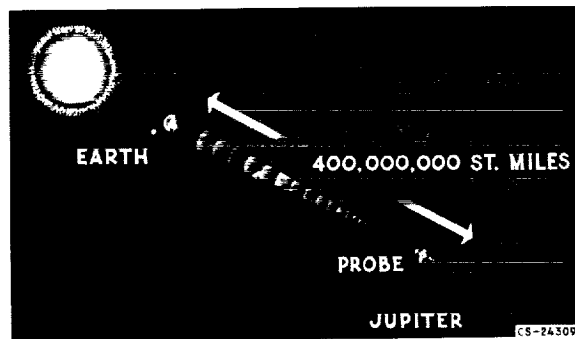


FIGURE 46-5.—Unmanned television probe of Jupiter. Estimated power requirement, 1 megawatt.

shows an unmanned probe to Jupiter for which the power requirement may be as high as 1 megawatt in order to send television pictures back to Earth.

The application that imposes the most difficult requirements on the powerplant is electric propulsion. Figure 46-6 shows one concept of a manned, electrically propelled, interplanetary spacecraft. The most prominent part of an electrically propelled vehicle is the radiator, which rejects the waste heat from the powerplant. For the vehicle shown, the total radiating area is 10,000 to 20,000 square feet. At the near end of the vehicle are the nuclear reactor

and shield. Behind them is the electrical generating machinery and the radiator. At the far end of the vehicle are the living quarters and the electric propulsors. The length of the vehicle is about 600 feet.

A round trip to Mars will take  $1\frac{1}{2}$  to 2 years and the powerplant will have to provide 10 to 30 megawatts of power continuously for this period. Furthermore, the powerplant will have



FIGURE 46-6.—Manned, electrically propelled, interplanetary spacecraft. Estimated power requirement, 10 to 30 megawatts.

to be very lightweight. Only nuclear power systems can fulfill these requirements.

### SOLAR CELLS

A. E. POTTER, JR. All scientific satellites that require power for more than a few months rely on solar photovoltaic cells. Silicon cells have been used exclusively up to the present, although other cell materials, such as gallium arsenide, may eventually be used. Although they are well suited for space use, solar cells could be improved in several areas. In this section are discussed some of these problem areas, specifically, radiation damage to solar cells and the complexity and weight of large solar-cell power systems.

An important problem facing the designer of solar-cell power systems intended to operate in space is radiation damage to the solar cells. The ultimate limit to the lifetime of spacecraft powered by solar cells is set by radiation damage, which occurs principally in the Van Allen belt. The procedure in the past has been to protect the solar cell by covering it with a quartz or sapphire window 10 to 30 mils thick. This protective covering has been sufficient to prolong the lifetime of the unshielded cell in

the heart of the Van Allen belt from a few days to months or years. This lifetime is sufficient for most purposes. The situation however, has been changed by the U.S. high-altitude nuclear detonation, Starfish, on July 9, 1962. This explosion injected large numbers of energetic electrons into the magnetic field of the Earth and formed a new radiation belt around the Earth. The altitude and the contours of the new radiation belt greatly resemble the natural Van Allen radiation belt. A significant difference between the old natural belt and the new artificial belt superimposed on it is that the new belt has about ten times as many energetic electrons as the old one. The new electrons are disappearing rapidly at low altitudes, but very slowly at high altitudes. The mean lifetime of the artificial belt is estimated to be between 10 and 100 years. Since the density of energetic electrons has increased by an order of magnitude, the lifetime of solar cells in the artificial radiation belt (which for convenience is called the new Van Allen belt herein) has decreased by an order of magnitude. Furthermore, this state of affairs is not temporary but will continue for a decade or more. The effect of the nuclear blast on solar-cell lifetime is shown in figure 46-7, where the lifetime (defined herein as the time required for solar-cell output to drop 25 percent) of an unshielded solar cell in the heart of the radiation belt is compared before and after the blast. Lifetime was reduced a factor of 10 by the nuclear blast. The reduction in cell lifetime was shown 3 days after the nuclear detonation, when the British satellite Ariel ceased to operate because of radiation damage

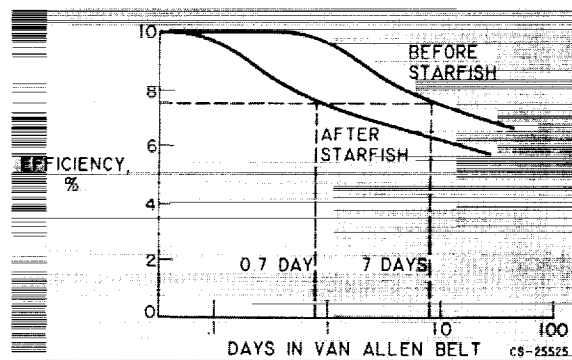
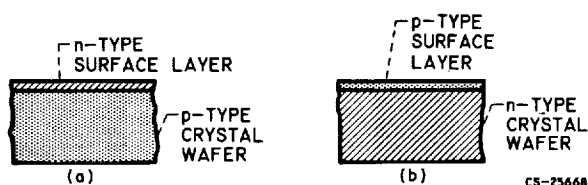


FIGURE 46-7.—Effect of nuclear detonation Starfish on lifetime of unshielded p-on-n solar cells.



(a) n-on-p cell. (b) p-on-n cell.

FIGURE 46-8.—The p-on-n and n-on-p type solar cells.

to the solar power supply. Shortly after, two other satellites ceased to operate for this same reason.

There are two ways in which this problem can be solved. The quartz or sapphire shield covers could be thickened. To be effective, however, they become so thick as to make the power system extremely heavy. A better solution is to use more radiation-resistant solar cells. Joseph Mandelkorn, formerly of the Signal Corps, now at Lewis, has discovered how to make radiation-resistant solar cells. These new cells are called n-on-p cells to distinguish them from the older p-on-n cells commonly manufactured. These two types of cells are illustrated in figure 46-8. The old silicon cell, the p-on-n cell, is made by diffusing boron into the surface of an n-type silicon crystal wafer to make a p-type layer on the wafer surface. Hence, a p-on-n cell. The new n-on-p cells are made by diffusing phosphorous into the surface of a p-type silicon crystal so as to make an n-type layer on the surface. Hence, an n-on-p cell. The radiation resistance of the new cells is shown in figure 46-9. In the figure, the lifetime in the heart of the artificial radiation belt for the old p-on-n cells is compared with that for the new n-on-p cells. The lifetime of the new cells is more than an order of magnitude longer than the old cells. Therefore, the lifetime of the new cells in the new radiation belt is comparable to the lifetime of the old cells before the nuclear detonation. The Bell Telstar satellite is equipped with these new cells, and its long lifetime is directly attributable to this fact. It is intended that future U.S. satellites shall be equipped with the new n-on-p cells. Meanwhile, our research on radiation-resistant solar cells continues. Possibilities that seem promising at present are as follows:

(1) Gallium arsenide solar cells: These cells appear definitely to be very resistant to

radiation damage, but are difficult to make with useful conversion efficiencies.

(2) Superpure silicon cells: Use of very pure silicon may make cells more resistant to radiation damage.

(3) Thin-film cadmium sulfide cells: These cells, while of low efficiency, seem to be resistant to radiation damage.

There are many potential uses for large solar-cell power supplies that yield 1 kilowatt or more of electric power. The fabrication of large solar-cell arrays, however, is both difficult and costly principally because of the small size of the cells. Cells are available in areas of only a few square centimeters. Hence, many thousands must be wired together to produce large amounts of power. It has been estimated that 30,000 cells would be required to make a 1-kilowatt array, and that the labor involved in assembling the array would cost in excess of a half-million dollars. Naturally, such an array is complex. Such complexity is very undesirable for any system intended to operate for years in space.

In addition to complexity, large solar-cell power systems are heavy. The silicon cells alone are quite lightweight, but by the time the cells have been shielded from radiation damage, wired together, and placed on a support the weight has increased considerably. An optimistic estimate of the weight of a 1-kilowatt solar-cell array is 100 pounds. A smaller weight would be very desirable.

A further difficulty with large solar-cell arrays is that of packaging them in rockets. Some means is required of folding the array

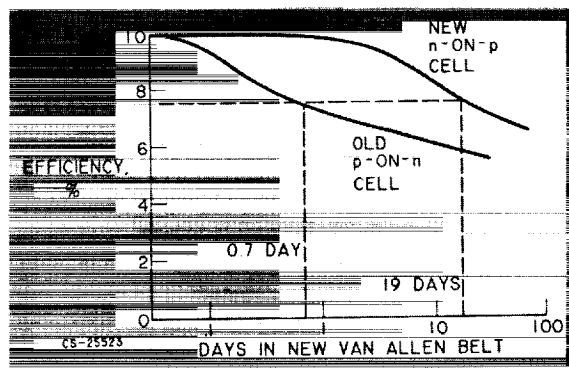


FIGURE 46-9.—Lifetimes in new Van Allen belt for unshielded p-on-n and n-on-p solar cells.

into a small volume for launch, followed by deployment of the array when orbit is achieved. Further undesirable complexity is introduced by this requirement.

A possible solution to the problems of complexity and weight may be found in the development of large-area thin-film photovoltaic cells. Such cells can be made by evaporation of thin layers of semiconductors onto thin flexible metal or plastic substrates. The familiar selenium cell as used in lightmeters is an example of a photovoltaic cell that is made in this way. Other materials, such as silicon, cadmium sulfide, cadmium telluride, or gallium arsenide can also be used. Thin-film cells are characteristically of low efficiency, not more than a few percent. Because they can be made very thin, however, they are lightweight. Another important advantage gained from the thinness is flexibility. Flexible cells can be rolled up or folded into small volumes suitable for rocket payloads. An additional major advantage of the thin-film cells is the simplicity with which large areas can be made. Evaporation processes are easily adaptable to making very large areas in a single operation. This possibility should greatly reduce the complexity and cost of a large power supply.

Research on such cells is being done at Lewis and is also being sponsored by NASA at non-government organizations. Work is going on with both gallium arsenide and cadmium sulfide

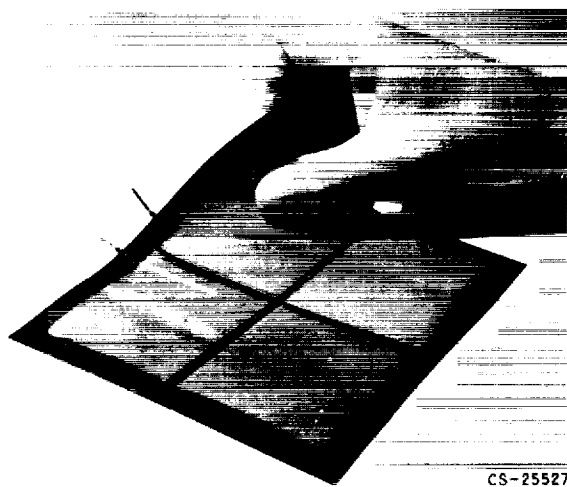
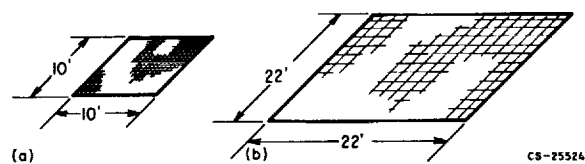


FIGURE 46-10.—Flexible thin-film cadmium sulfide photovoltaic cell.



(a) Silicon cell array. (b) Cadmium sulfide cell array.

FIGURE 46-11.—Comparison of 1-kilowatt silicon solar-cell panel with 1-kilowatt cadmium sulfide film solar-cell panel.

film cells. Promising thin-film cadmium sulfide cells have been made by the Harshaw Company. An example of one of these cells is shown in figure 46-10. This cell is about 6 inches square and has an efficiency of about 1.5 percent. It is thin (about 0.008 in.) and flexible. Cells of this kind have been made with efficiencies of over 2.5 percent. At the present state of the art, thin-film cadmium sulfide solar cells that are 2 percent efficient, flexible, and lightweight (weighing approximately 70 lb/kw of power output) can be made in large numbers. The unshielded lifetime of such cells is estimated at 100 to 1000 days in the heart of the new radiation belt.

It is interesting to compare a large silicon solar-cell array with a large cadmium sulfide film cell array. This is done in figure 46-11. A 1-kilowatt silicon cell array will weigh of the order of 100 pounds and occupy an area of about 100 square feet. About 30,000 cells are required. A 1-kilowatt cadmium sulfide film cell array will weigh about 70 pounds and occupy an area of about 500 square feet. The larger area is required because of the low efficiency of the cells. About 2000 film cells 6 inches square are required. It appears that significant savings in weight and complexity of large arrays can be achieved with the use of cadmium sulfide film cells. The larger area required for the film-cell array is offset by the fact that the film cells are flexible enough that folding into small volumes for launch appears possible. This problem of storage in the rocket with subsequent deployment in space, however, is a major one that must be solved before large power supplies are practical.

Solar-cell arrays are unique in that they provide power at a constant level and only in sunlight. If large peaks of power, or operation in

darkness are required, batteries must be used for energy storage. These batteries may weigh as much as the solar-cell array itself. Therefore, an important problem area for solar-power supplies is the energy-storage system.

### BATTERIES

**HARVEY J. SCHWARTZ.** In almost every space vehicle launched to date, batteries have been used for energy storage. This energy storage capability is used in several ways.

Secondary batteries, that is, those which may be recharged, like the battery in an automobile, are used in combination with solar cells for orbiting satellites. The orbital paths of these vehicles pass from sunshine to shade on each trip around the Earth. The solar panels supply power during the sun portion of the orbit and additional energy to recharge the batteries. During the shade period, battery power is expended.

Primary batteries, those which are used once and then discarded, as a flashlight cell, supply all the power requirements of the Mercury capsule in manned orbital flight. Batteries are used to supply power for instrumentation, telemetry, communications, and general capsule housekeeping.

Batteries also find application where surges of power are required. Typical of this application is the Ranger vehicle shown in figure 46-12. Here, the solar panels are the main source of power. Battery power is used during the launch phase of the mission and for deployment and orientation of the solar panels. The batteries are then recharged and maintained in a charged state until required to meet peak power-load conditions later in the mission. Thus, batteries are actually used to supplement

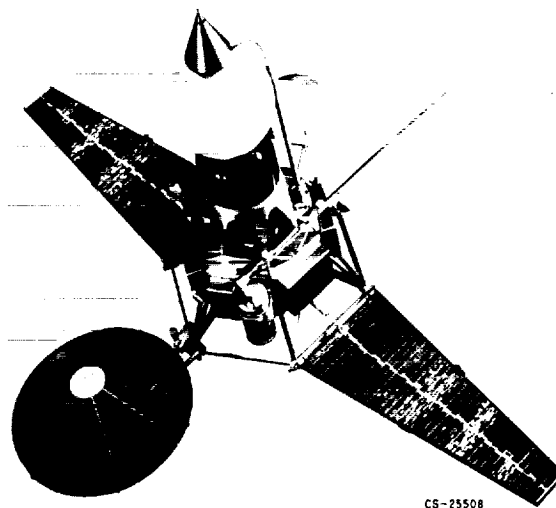


FIGURE 46-12.—Ranger 3 spacecraft.

the power output of the solar array, which results in a smaller, lighter power system.

Smaller and lighter are key words in the design of power systems for space use. The energy densities available from conventional batteries operated at low discharge rates are compared in table 46-I. Several significant points are evident from this table. The most commonly used batteries for space purposes are alkaline electrolyte cells that use nickel-cadmium, silver oxide-cadmium, and silver oxide-zinc as the electrode reactants. Of concern here are energy outputs ranging from 15 to 80 watt-hours for each pound of battery carried on the mission. In addition, a great difference exists in the ability of these cells to withstand the repeated charge-discharge cycling required for secondary-battery applications.

In selecting the proper cell for a particular mission requirement, it is necessary to consider

TABLE 46-I.—*Energy Densities Available from Conventional Batteries*

System	Primary battery			Secondary battery	
	Power density, watt-hr/lb			Actual power density, watt-hr/lb	Shallow discharge life, cycles
	Theory	Actual	Expected maximum		
Zinc-silver oxide, Zn/KOH/AgO.....	193	80	95	40	80-100
Silver-cadmium, AgO/KOH/Cd.....	118	33	40	30	2000-3000
Nickel-cadmium, NiO OH/KOH/Cd.....	99	17	20	7-10	1000-11,000

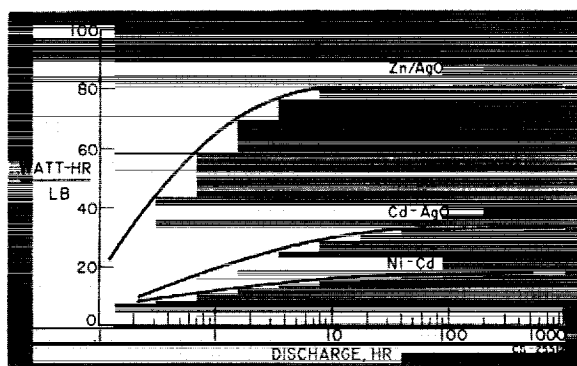


FIGURE 46-13.—Variation of primary-cell capacity with discharge rate at a temperature of 80° F and a voltage drop of 20 percent.

factors other than capacity and cycle life. Characteristics such as storage life, temperature stability, and the effect of discharge rate on capacity must be considered. In general, increases in temperature or discharge rate will decrease capacity and cycle life. Likewise, increasing the depth of discharge beyond the design level will limit cycle life in a secondary battery. One such effect, the variation of capacity with discharge rate is illustrated in figure 46-13. Here, the capacity in watt-hours per pound is plotted against the discharge time, which is the time required to discharge to 80 percent of the initial potential. Capacity is lowest at the high discharge rate portion of the curve and reaches a maximum value at discharge times from 10 to 100 hours.

The problem areas in conventional batteries are readily apparent. Efforts are being made to produce cells with increased capacity under rapid deep discharge conditions, better shelf life, and more favorable charge-discharge characteristics over extended cycling. In addition, new systems that have theoretical energy densities of 500 to 2500 watt-hours per pound are being explored. Realization of only a small fraction of these yields will be marked improvement over today's batteries.

Batteries are not exotic power sources, but they will continue to play an important role in space-power systems. They will be used, even when far more advanced power systems become available. They offer a safe reliable power source for use prior to startup of the main system, for meeting transient load peaks in mis-

sion power profiles, and for emergency power supplies.

### RADIOISOTOPE POWER SUPPLIES

A. E. POTTER, JR. When small amounts of power are required for longer times than available from chemical batteries and solar cells cannot be used, radioisotope heat sources are useful. Radioisotope heat sources may be combined with a thermoelectric converter to produce a source of electric power suitable for use in space. The odd-numbered Snap (Systems for nuclear auxiliary power) generators are this type of power supply. For example, Snap-3 is a 3.3-watt generator, which uses polonium 210 as the heat source and lead telluride elements as the thermoelectric converter. Radioisotope-thermoelectric generators have the disadvantage that they are heavy, 1000 pounds or more per kilowatt, and hence, are not useful for large powers.

A novel idea for the use of radioisotopes is the radioisotope balloon for generation of high voltages. This device is discussed in the paper by Edmund E. Callaghan.

### FUEL CELLS

HARVEY J. SCHWARTZ. If a battery is the power system of today, the fuel cell will be the power system of tomorrow's missions. This is pointed out clearly by the fact that NASA has selected fuel-cell power systems for both the Gemini and Apollo missions.

A fuel cell is an electrochemical device in which the reactants and the reaction products are not stored within the case as they are in a battery. In a fuel cell, reactants are stored separately and fed continuously to the electrodes, and the reaction product is removed continuously. As long as these processes continue, power is generated.

Fuel cells may be classified in a number of ways. There are primary cells, in which fuel and oxidant are continuously used up, and regenerative systems, in which the reaction product is dissociated to regenerate the reactants. Systems may be classified as low-, medium-, or high-temperature according to the cell operating temperature involved. Electrolytes may be aqueous solutions (27 percent potassium hy-

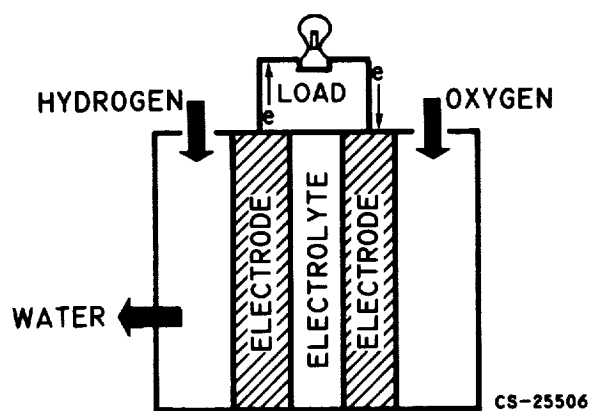
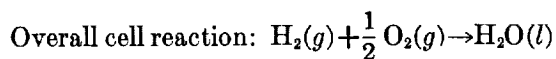
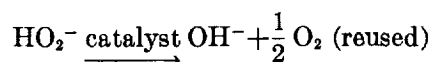
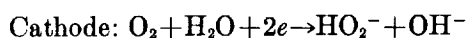
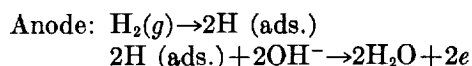


FIGURE 46-14.—Typical hydrogen-oxygen fuel cell.

dioxide is typical), solid electrolytes such as ion-exchange membranes, or fused salts. Electrolytes that are liquids may reside freely between the electrodes or be retained in a suitable matrix. In regenerative systems, the required dissociation may be achieved by adding either thermal, electrical, or photochemical energy.

Primary systems using hydrogen and oxygen as reactants are of greatest interest today. The reason is simple: We know the most about these systems and they work the best. A typical hydrogen-oxygen fuel cell is shown in figure 46-14. A single cell looks much like a battery. It consists of a pair of electrodes between which is an electrolyte. The electrolyte must be not only an ionic conductor but also an electronic insulator. The gases are admitted to their respective electrodes and ionize. Electrons are released at the hydrogen electrode, travel through an external

load to do useful work, and then return to the cell at the oxygen electrode. The simplified individual electrode reactions for an alkaline cell are as follows:



These reactions differ slightly for acid electrolyte cells, but the overall reaction,  $\text{H}_2 + \text{O}_2 \rightarrow \frac{1}{2} \text{H}_2\text{O}$ , remains the same.

It would appear then that all hydrogen-oxygen fuel cells should be the same. They do share common problems of rejecting the heat formed during cell operation and removing the reaction product water.

There are a large number of possible combinations of electrolyte, electrodes, and operating conditions that can be combined to form a workable hydrogen-oxygen fuel cell. Each combination leads to different solutions to the problems cited before. To illustrate this point, consider the ion-exchange membrane fuel-cell system being developed by the General Electric Company for the Gemini mission and the modified Bacon-type fuel-cell system designed by Pratt & Whitney Aircraft Company for the Apollo mission. A comparison of these two systems is given in table 46-II.

TABLE 46-II.—Comparison of Hydrogen-Oxygen Fuel-Cell Systems

Type of system.....	Modified Bacon cell (Apollo).....	Ion exchange membrane cell (Gemini)
Operating temperature, °F.....	500	140
Operating pressure, lb/sq in. gage..	60	>10
Electrolyte.....	Concentrated potassium hydroxide (solution)	Cation exchange membrane (solid)
Electrodes.....	Sintered dual-porosity nickel.....	Woven metal screen
Operating current density, amp/sq ft	200	40
Water removal.....	Evaporation into circulating gas stream	Capillary transport
Heat rejection.....	Circulating gas stream.....	Circulating coolant to individual cells

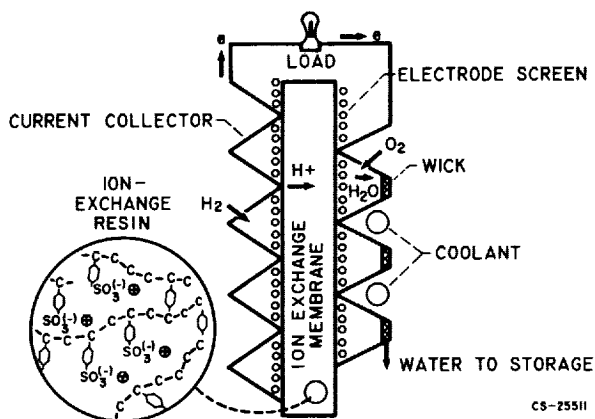


FIGURE 46-15.—Ion-exchange-membrane cell for space application.

The values shown in the table are representative of these systems but are not necessarily design points for the respective missions.

The ion-exchange-membrane fuel cell designed for space use is shown in figure 46-15. The electrolyte consists of a solid ion-exchange resin; a sulfonated polystyrene is shown. The resin has the property of selectivity; it transports cations and does not transfer anions. Hydrogen gas ionizes at its electrode; the ions formed travel through the electrolyte, and then combine with oxygen to form water at the oxygen electrode. Heat is removed by circulating a liquid coolant to each cell. A woven cloth wick is placed in the channel of each oxygen-electrode current collector. Since the water formed has an appreciable vapor pressure at the cell operating temperature, water vapor is transported to the wick, where it condenses.

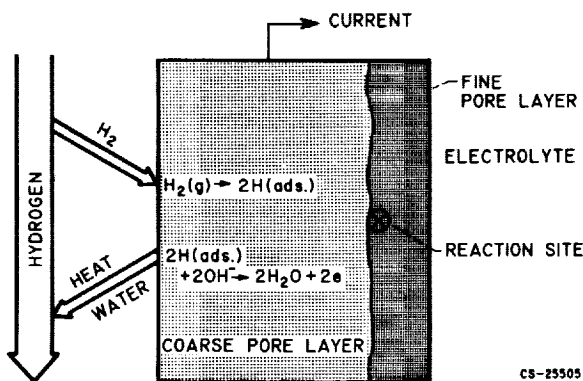


FIGURE 46-16.—Hydrogen electrode processes in Bacon-type fuel cell.

Capillary forces then remove the water to storage.

The modified Bacon-type fuel-cell system to be used on the Apollo mission is a medium-temperature system. The electrolyte, a highly concentrated potassium hydroxide solution, is contained between sintered porous nickel electrodes. In this alkaline cell, water is formed at the hydrogen electrode, and the heat- and mass-transfer operations occur here as shown in figure 46-16. Excess hydrogen gas is circulated past the back face of the porous electrode. Water formed by the cell reaction is evaporated into the gas stream. The stream is cooled to condense the water and the two phases are then separated. Water is pumped to storage while the gas stream is recirculated.

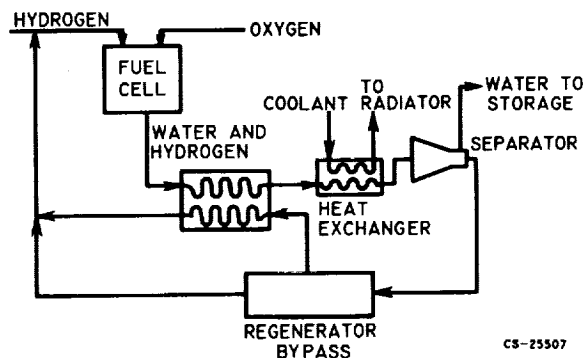


FIGURE 46-17.—Schematic representation of Bacon-type fuel-cell system.

A schematic diagram of the Bacon-type system is shown in figure 46-17. The hot, moist hydrogen stream leaving the cell warms the recirculating gas stream and thus conserves heat. The stream is cooled to condense the water; the waste heat is transferred by a coolant to a space radiator for rejection. The two phases are then separated in a rotating separator capable of operating at zero gravity. The circulating gas serves as a means of transferring heat to the system radiator.

As different as these systems are, they offer the same advantages for their respective missions. The weight of the system and fuel required is considerably less than the weight of the batteries needed to produce the same power output. In addition, both systems are capable of producing potable water as a byproduct,

which can be consumed by the astronauts. This byproduct yields a savings of several hundred pounds of payload on a mission of the Apollo type. Since the Apollo mission as originally conceived called for landing of the fuel cell on the lunar surface, a medium-temperature system has definite advantage with respect to heat rejection. The Gemini mission permits use of a low-temperature fuel cell. Advantage can therefore be taken of the lighter weight offered by the ion-exchange membrane system.

Other types of fuel cells are under active investigation. Regenerative fuel cells are of interest. In these cells a simple energy source such as heat, light, or electricity is used to dissociate the cell product to reactants for recirculation. Since fuel cells offer a higher energy density than batteries, they may some day replace batteries as an energy storage means for orbiting satellites. Electricity from the solar array could be used to electrolyze the water formed during the shade part of the orbit when the fuel cells are in use.

Another interesting facet of electrochemical power generation is the biological generator. Biochemical fuel cells have received much publicity in the popular press lately. While it is unlikely that the results obtained to date justify the amount of attention received, biological systems may some day find use where long life, very-low-power output systems are required.

Fuel cells offer attractive power systems where moderate power outputs are required over periods of days to several weeks. They offer a simple static generating device with highly efficient fuel utilization. They will continue to be important over the next several years.

#### CHEMICALLY FUELED ENGINES

DANIEL T. BERNATOWICZ. Several types of chemically fueled engines are being considered for applications similar to those for fuel cells. The weight of these engines is estimated to be considerably less than the weight of the fuel cells, but they are less efficient and, therefore, consume more reactants. For periods of operation up to a few days, the combined weight of engine and reactants is estimated to be less than that of a fuel cell and its react-

ants. An engine could be used as a stand-by power unit to provide power while repairs are made on the main power system, as the main power supply on a vehicle like the Apollo lunar landing module, or as a portable power unit during lunar surface operations, for example, for digging postholes.

#### SOLAR HEAT COLLECTORS

NEWELL D. SANDERS. Stored chemical energy is not generally practical as a sustaining power source where the mission duration exceeds 2 weeks because of the great weight of reactants required. Examples of the longer duration missions are orbiting laboratories, manned lunar bases, and communications and weather satellites. The lifetimes of these missions are measured in months or years. For these and similar missions, solar and nuclear power are needed.

Perhaps the most important problem connected with the use of solar energy is the collection of the energy. The Sun's radiation at the Earth's orbit amounts to 125 watts per square foot. The efficiency of conversion may lie in the range between 3 percent to better than 15 percent. To produce 5 kilowatts, the Sun's energy must be collected from an area lying in the range of several hundred to more than 1000 square feet. The launching of such large-area reflectors can be accomplished only by using folding structures which can be placed in small packages for launching and later deployment in space.

The use of thin-film solar cells on a flexible support, as described earlier, is a very promising technique for producing power in the range of several tens of kilowatts. If good new ideas are forthcoming concerning deployment and orientation of acres of this material, power in the megawatt range may be possible.

Collectors that concentrate the Sun's energy are required for thermodynamic or thermionic power systems as they are now conceived. A folding collector for the 3-kilowatt Sunflower system is shown in figure 46-18. The diameter is 32 feet. It consists of rigid petals made of 3-mil aluminum skin bonded to a 1/2-inch honeycomb core. The inner surface is formed to a paraboloid and is polished. The assembled

mirror focuses the Sun's image into the mercury boiler (not shown) of the power-generating system. The petals are hinged to the frame at the center and can be folded into a 10-foot-diameter shroud for launching. The specific weight of this collector is 0.26 pound per square foot. It is being made by the Thompson Ramo Wooldridge Corporation.

A smaller 10-foot-diameter folding petal reflector using a truss-and-skin-type structure is also being constructed by the Ryan Company. Its specific weight is 0.37 pound per square foot.

A small 4-foot-diameter folding Fresnel reflector has been made by the Allison Division

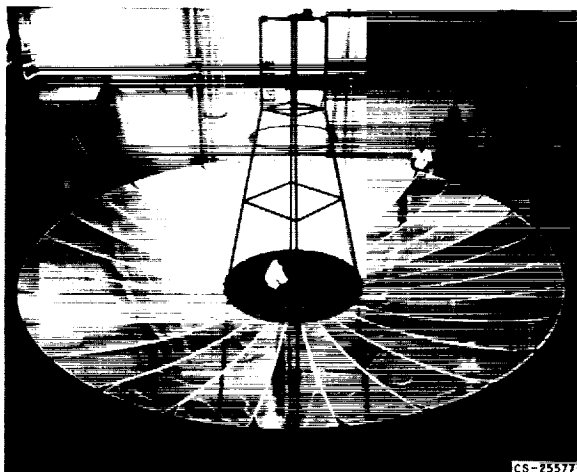


FIGURE 46-18.—Furlable petal collector of aluminum foil bonded to honeycomb core.

of General Motors. The Fresnel reflector resembles a serrated flat plate. This flat shape eases the problem of folding and storing and the serrations give rigidity to the reflector. The Allison unit is made by depositing nickel on a master and then coating the reflecting surface with aluminum. Its specific weight is 0.46 pound per square foot.

Collectors made of flexible inflatable plastic films are especially attractive because of the potential capability of very large size and small storage volume during launch. Figure 46-19 shows such a collector made by Goodyear. It consists of segments or gores made of preshaped Mylar envelopes. The bundle at the bottom of the photograph illustrates the size of the collapsed unit. After launching into space, a



FIGURE 46-19.—Inflatable rigidized collector of foam-backed aluminized Mylar.

foaming plastic is injected into the gores and the collector is caused to take the desired shape. The rigid foam maintains the extended shape of the collector. The collector shown here is 10 feet in diameter and the specific weight is estimated to be 0.2 pound per square foot for a 30-foot collector.

The accuracies of the collectors, just discussed, are expected to be satisfactory when the collectors are used with heat engines operating at relatively low temperatures near 1300° F. In the case of thermionic conversion devices, however, much higher temperatures are required and reflectors of much greater accuracy are needed. Small fixed reflectors might be de-

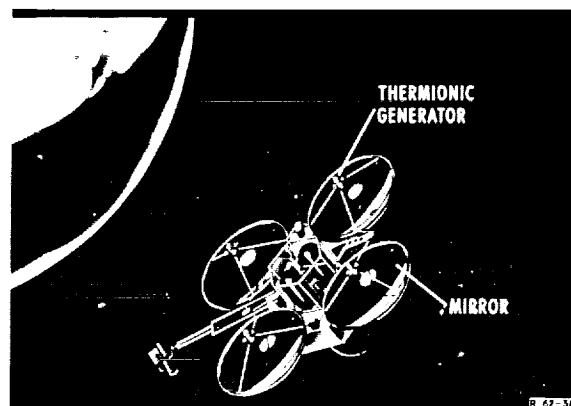


FIGURE 46-20.—Solar thermionic power system.

veloped with the desired accuracy. A 9½-foot rigid metal mirror is under development by the Electro-Optical Systems Company. Several of these mirrors might be clustered as shown in figure 46-20 to give the desired power.

In addition to the highly accurate shape required for the high-temperature systems, accurate pointing systems are required.

#### NUCLEAR REACTORS FOR SPACE POWER

**CHARLES A. BARRETT.** A promising heat source, especially in the kilowatt and megawatt range, for a Rankine cycle system is an alkali-metal, cooled nuclear reactor. In most of the current concepts, a reactor loop is coupled to the Rankine cycle working loop through the heat exchanger.

Fortunately for the space program, alkali-metal reactor technology has been developed for various military and commercial applications so that it can be readily adapted for space nuclear powerplants. These reactors fall into two general classes: (1) a low-temperature system with a fluid-out temperature as high as 1400° F and (2) a high-temperature system with a fluid-out temperature close to 2000° F. The cores in such reactors are quite small; they range from less than 1 foot in diameter (if spherical cores are used) in the lower-temperature reactors to almost 2 feet in the advanced reactors.

The low-temperature system uses either a sodium-potassium alloy or sodium as the coolant and conventional alloys such as stainless steels and nickel-base alloys as the cladding and piping material. The fuel and moderator material is also fairly conventional. A major problem in such systems is to keep the oxygen and carbon contamination low enough in the reactor fluid that corrosion and subsequent plugging is not a problem. This involves proper purification analysis and handling of the alkali metal prior to loading the system and generally trapping the impurities in the metal or gettering the impurities while the system is in operation. Sources of contaminants within the system such as carbon in high-carbon steels must also be minimized. Because the problem can be so severe, continual monitoring of the system, usually by a plugging meter, is neces-

sary. If such precautions are taken, these systems are very reliable. Current commercial powerplants are using this general type of reactor, such as Hallam in Nebraska and Fermi in Michigan, which are designed for many years' operation (though attended)—much longer than the 10,000 hours for space power systems. The original Sea Wolf submarine reactor was also this same type and was operated successfully to design conditions.

Another problem at temperatures above 1200° F, unique to the space powerplant reactors that are to be hydride moderated, is dissociation of the hydride moderator into free hydrogen. Some sort of coating is required to minimize diffusion.

The advanced alkali-metal reactor was designed originally for the now defunct Aircraft Nuclear Propulsion program and was still in an early state of development. The originally designed lifetime was much shorter—of the order of 1000 hours. Because of the very high operational temperatures, a new fluid, lithium, had to be used as the reactor coolant. Because operating temperatures were close to 2000° F, conventional alloys had neither the strength nor corrosion resistance to hold up for even a few hours. In a sense this was fortunate because the system was forced to use and develop the refractory metal columbium (chosen mainly because of its low capture cross section for thermal neutrons) which was a rare metal up to that time, 1956. It appeared that columbium had sufficient strength and corrosion resistance but also some limitations, which made development of such a system lengthy and costly. This advanced reactor now rechristened Snap-50, although quite promising, is far from being truly operational.

Another possibility would be to use gas-cooled reactors with either helium or argon as the coolant. Little work has been done by the AEC on developing small compact gas-cooled reactors. Most of the development has been done on very large reactors for very high power levels. Scaling down both in size and power to compete with liquid-metal-cooled reactors does not seem likely at this time.

The obvious problem in using a nuclear reactor, especially where human beings might be

in proximity, is that of shielding them from harmful radiation. The design of such a system must take this into consideration. The required shield is very heavy. Its weight approaches 20 percent of the system weight. Wide separation of crew and reactor helps to minimize shield weight.

Additional radiation-hazard problems are associated with launch and rendezvous. These problems must be considered in the selection of the power system.

### LOW-POWER RANKINE CYCLE SYSTEMS

THOMAS P. MOFFITT. Either a reactor or a solar heat source can be used for the Rankine power conversion system. Figure 46-21 is a schematic diagram of a typical Rankine cycle utilizing a reactor as the heat source. The example shown is a two-loop system: a liquid loop using a liquid metal as the heat-transport fluid between the reactor and the boiler, and a two-phase loop where a liquid metal is vaporized, expanded through the turbine producing power, condensed in the radiator, and pumped back to boiler pressure by the condensate pump.

The main advantage of the Rankine cycle is that high conversion efficiencies are obtainable, because both heat-transfer processes can be made to take place at essentially constant temperature. The cycle can thus approach Carnot efficiency, which is the theoretical limit between any two given temperatures.

The reliability and life requirements of this type of system are very stringent. The equip-

ment may have to run for years with unattended operation. The principal disadvantages of the Rankine cycle are related to the life problem. These disadvantages are the use of corrosive liquid metals as working fluids and the necessity of using rotating components in the conversion system. The implied problems become more acute with increasing temperatures, which are desired for the high-power systems of the future.

Although the Rankine cycle is attractive in the multimewatt range, it is competitive in the relatively low-power level, the multikilowatt range.

Systems under development in the low-power range include both nuclear and solar heat sources. Snap-2, which is a nuclear Rankine system, uses NaK, a sodium and potassium alloy, as the reactor coolant liquid. The NaK, then, is the heat source to boil mercury, which drives the mercury-vapor turbine. It is designed to produce 3 kilowatts of electric power and operate with a maximum NaK temperature of 1200° F at the reactor outlet. The only other nuclear Rankine space powerplant under development is Snap-8, which is similar to Snap-2, but is to produce 30 kilowatts of electric power and operate at a higher reactor-outlet temperature, 1300° F compared with 1200° F for Snap-2. An example of a solar Rankine space cycle system under consideration is Sunflower, which is shown in figure 46-22. The system utilizes a solar collector to concentrate solar energy to a mercury boiler. Because Sunflower must operate continuously in the sun or shade, a stored heat source is required to boil the mercury during shadow time. Lithium hydride is used for this purpose. The boiler is contained within the lithium hydride thermal storage medium, which absorbs the collected heat during sun time and transfers its latent heat of fusion to the mercury while it freezes during shadow time. The system is to produce 3 kilowatts of electric power and to operate at a maximum mercury-vapor temperature of 1250° F. The mercury technology and alternator from Snap-2 are to be used in Sunflower with minor changes in the power-conversion system.

In the development of the Snap-2 and Snap-8 systems, several major problems have arisen

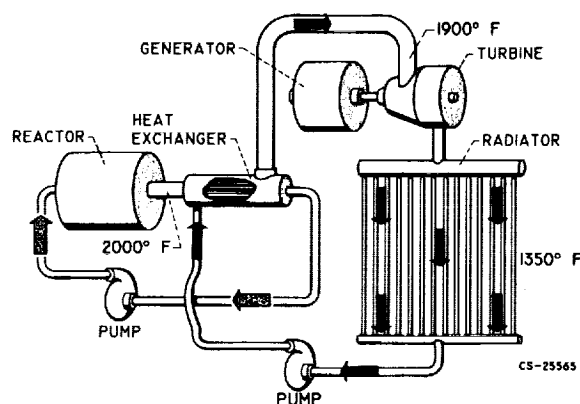


FIGURE 46-21.—Rankine cycle space power system.

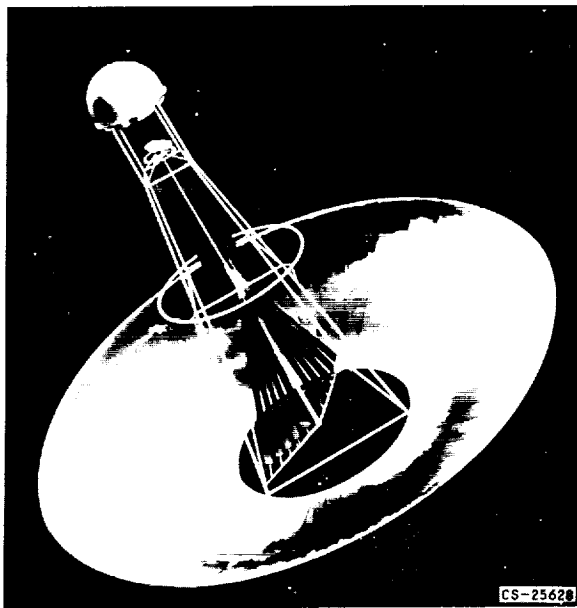


FIGURE 46-22.—Sunflower.

that were either unforeseen or of unforeseen severity. These problems are generally related to (1) bearing integration into a complex thermal package, (2) containment-material problems involving corrosion and system contamination, and (3) boiling heat transfer as affected by tube wetting, temperature, and pressure-drop distribution.

### BRAYTON CYCLE SYSTEMS

DANIEL T. BERNATOWICZ. Another cycle being given serious consideration is the regenerative Brayton cycle. Figure 46-23 depicts schematically a Brayton cycle space power-

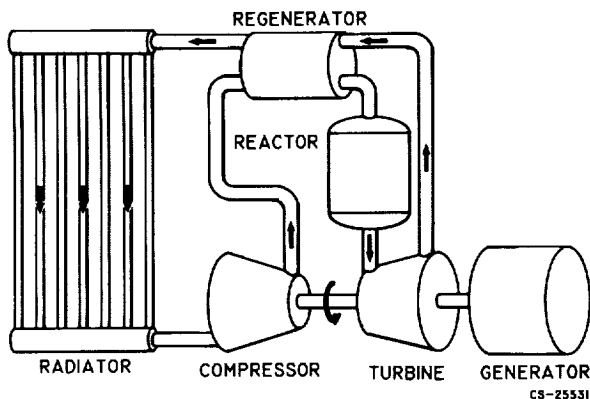


FIGURE 46-23.—Regenerative Brayton cycle space power system.

plant. In the Brayton cycle the working fluid remains gaseous throughout the cycle. Cold gas is compressed in the compressor and passes through a regenerator in which it is preheated by gas from the turbine exhaust. The gas is then heated to its maximum temperature in the reactor and is expanded through a turbine that drives the compressor and an electrical generator. The gas then passes through the regenerator, where it gives up some of its heat to the gas leaving the compressor. More heat is given up in the radiator, and this heat is radiated to space. The cold gas enters the compressor and passes through the cycle again.

A nuclear reactor is shown as the heat source; gas passes through the reactor core. If a gas-cooled reactor is not suitable, a liquid-metal-cooled reactor could be used, with the liquid metal heating the gas in a heat exchanger. Also, a solar or chemical heat source could be used if either fitted the application better.

For the same temperature limits the Brayton cycle is less efficient and requires a larger radiator than the Rankine cycle. For comparable performance, the Brayton cycle system must operate with a higher maximum temperature and would impose more difficult requirements on the heat source. The Brayton cycle is also very sensitive to compressor and turbine performance and pressure losses in the system, more so than the Rankine cycle. The Brayton cycle system is estimated to weigh more than the Rankine cycle system. For nonpropulsive power applications, however, the weight of the powerplant, although important, is not of overriding importance. The absence of zero-gravity problems with a single-phase fluid, the lack of corrosion if an inert gas is used, and the large backlog of experience with turbomachinery suggest that quick development of a reliable Brayton system may be possible. A decision on whether to use a Brayton system will depend on the penalties in system weight and radiator size and on the ease of development relative to a Rankine system.

### POWER FOR ELECTRIC PROPULSION

DANIEL T. BERNATOWICZ. It was pointed out earlier that very lightweight long-lived powerplants capable of furnishing tre-

mendous amounts of power will be required for electric propulsion of manned interplanetary spacecraft. Before these powerplants and associated problems are described, an indication of why there is enough interest in electric propulsion to warrant undertaking such a difficult course is appropriate.

The basic motivation can be seen from a simple consideration of rocket propulsion. Chemical rockets expel a large mass of material at moderate velocities. As the missions become more difficult, the mass of propellant becomes a very large fraction of the mass of the entire vehicle. Obviously, the way to improve the situation is to increase the velocity of the expelled propellant, but in ordinary rockets the velocity is limited by the temperature to which the propellant can be raised. For a given temperature limit, the velocity is higher for propellants of low molecular weight. One improvement over ordinary chemical rockets is the nuclear rocket, in which hydrogen is heated by a nuclear reactor and expelled. In this system, the maximum velocity is limited by the temperature that the reactor can tolerate.

Charged particles can be electrically accelerated to very high velocities, up to near the speed of light. With electric acceleration, the propulsion problem takes on different aspects. Because the kinetic energy in the exhaust rises as the square of the velocity and the thrust only as the first power, the power added to the stream per pound of thrust increases linearly with velocity. In order that the power requirements be reasonable, low-thrust rockets can be used, and the mission objectives must be achieved by operating the thrusters for very long periods, perhaps continuously throughout the mission. In fact, for practical vehicles the thrust is so low that the acceleration is only  $10^{-3}$  to  $10^{-4}$  g. Such vehicles must be launched into orbit by chemical or nuclear rockets and then will proceed to the planets using electric propulsion.

Figure 46-24 shows the results of a study of a mission to send seven men to Mars. A nuclear-rocket vehicle is compared with an electrically propelled vehicle, both starting from an orbit around Earth. Initial gross weight of the vehicle is presented against the time required to perform the mission. For a mission time of

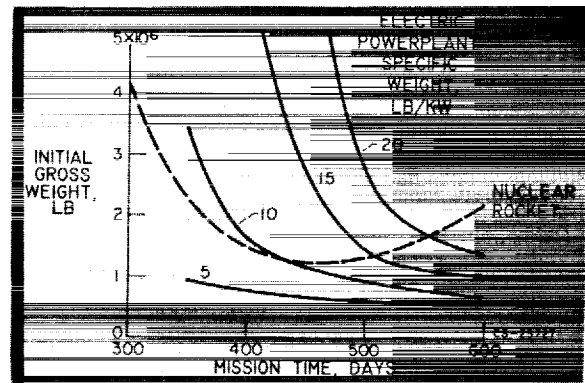


FIGURE 46-24.—Study of seven-man mission to Mars.

about 450 days, the powerplant specific weight must be 10 pounds per kilowatt or less to be superior to the nuclear rocket. If longer mission times can be tolerated, heavier powerplants can be used. Then, however, the powerplant must operate for a longer period of time and the low specific weights are more difficult to achieve. The power level required is 10 to 30 megawatts.

The specific weights shown in this figure are extremely low. The specific weights of systems under development, for example, Snap-2, Snap-8, and Sunflower, range from 70 to 250 pounds per kilowatt. Although enough information is not available to make accurate weight calculations for the advanced systems, studies indicate that such low weights may be possible, but only after enough technology is acquired to permit highly refined engineering design. Only two systems look attractive for this application, the nuclear Rankine turbogenerator system and the thermionic reactor system.

#### HIGH-POWER RANKINE CYCLE SYSTEMS

**THOMAS P. MOFFITT.** Consider the high-power Rankine conversion system utilizing a reactor as the heat source. Such a closed cycle can reject waste heat to space only by radiation, which is an inefficient method from area considerations. Furthermore, the best systems available must reject more than 75 percent of the reactor thermal power as waste heat. Consequently, the radiators for large power systems become massive and may constitute up to 50 percent of total system weight. Therefore, a system is required to maintain this weight with-

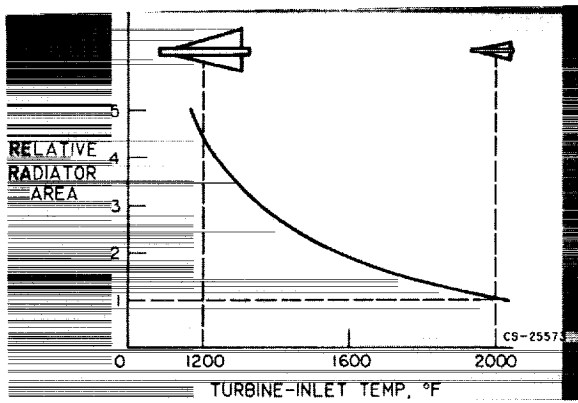


FIGURE 46-25.—Effect of turbine-inlet temperature on radiator area.

in reason. Of the systems available, the Rankine cycle turboelectric system is the only one likely to yield lightweight systems in the near future. The principal unknown in the field of radiator design is the meteoroid damage and protection required. This subject is discussed in the paper by Seymour Lieblein.

The necessity of minimizing radiator weight specifies certain requirements on the system:

(1) The system must operate at extremely high temperatures, 2000° F and higher. Figure 46-25 shows the effect of turbine-inlet temperature on relative radiator area, which is the parameter used to describe radiator weight. More than a fourfold difference in area exists between turbine-inlet temperatures of 1200° and 2000° F. This difference is due to the fact that radiation area is inversely proportional to the fourth power of the absolute radiation temperature. This fact, then, indicates the need for high system temperatures to achieve low system weight. The upper limit on temperature would be limited by either the reactor or the rotating components within the turbine.

(2) The system must use alkali metals as the working fluid. These metals appear to be the most attractive fluids from considerations of such things as heat-transfer characteristics, critical temperature, vapor pressure, and thermodynamic properties.

(3) Refractory-based alloys must be used as the fluid-containment material. At the extreme temperatures involved, the refractories appear to be the best materials to retain strength prop-

erties and also afford corrosion resistance to the alkali metals.

These requirements greatly magnify and generate new problems not encountered in the development programs under way in the low-power field, such as the Snap programs previously discussed. The problems result mostly from the higher temperatures involved and cover both the heat-transfer processes and the rotating components of the Rankine conversion system.

### Heat Transfer

Although the alkali metals have long been recognized for their excellent heat-transfer characteristics, the data resulting from their use have been largely restricted to single-phase liquid flow at temperatures below 1600° F.

Of more significance is the lack of data for two-phase heat transfer, notably forced-flow boiling. In the nucleate boiling regime, where very high heat fluxes are obtainable, the only data available are for nonflowing or pool boiling at temperatures less than 1600° F. Even here, the data can be scattered as much as an order of magnitude. There are no known data available for film boiling of the alkali metals, nor for the critical heating rate in the transition from nucleate to film boiling.

The two-phase problem is further complicated by the requirement of zero-g operation in space. Such problems as flow stability, phase separation, and keeping the desired phase on the heat-transfer surface are magnified. Techniques under investigation include the use of twisted ribbons and wires to sling the liquid phase outward to the heater surface, the generation of vapors by flashing centrifugal separators, and the use of liquid condensers.

There are extensive research programs under way at government laboratories, universities, and within the industry. These projects are expected to provide much high-temperature heat-transfer data in the next 2 to 3 years.

### Rotating Components

*Turbine.*—There are three parameters associated with the turbine that have a gross effect on the radiator weight. These parameters are turbine-inlet temperature, turbine efficiency,

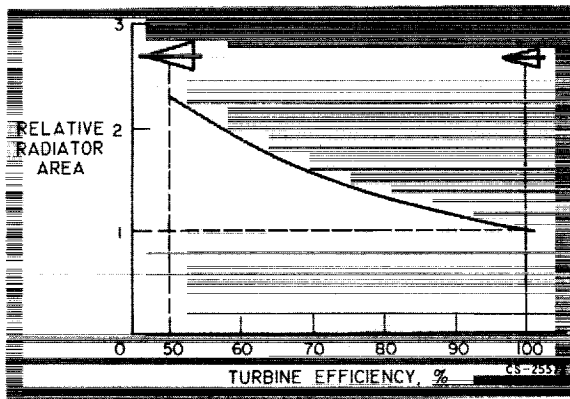


FIGURE 46-26.—Effect of turbine efficiency on radiator area.

and the condition of the vapor entering the turbine. It has previously been shown that more than a four fold difference in radiation area exists with an 800° F difference in turbine-inlet temperature, which indicates the need for high turbine temperatures.

The effect of turbine efficiency on radiator area is shown in figure 46-26. This figure shows the change in required relative radiator area for constant system power output at varying turbine efficiencies. As turbine efficiency increases from 50 to 100 percent, radiator area decreases by a factor of about  $2\frac{1}{2}$ . In view of the massive size of the radiator, it is apparent that high-performance turbines are a prerequisite to lightweight systems.

The condition of the vapor as it enters the turbine has an important effect upon the radiator weight. The vapor can either be superheated above its boiling temperature, or it can

be saturated, that is, at its boiling temperature. At the saturated condition, the vapor will start to condense as soon as the pressure drops during the turbine expansion process. For a fixed limiting turbine-inlet temperature, figure 46-27 shows the effect of using saturated or superheated vapor at the turbine inlet. A radiator area value of 1 represents a condition of saturated vapor at the turbine inlet. Increasing superheat from the saturated-vapor condition has a marked effect. For example, reducing turbine moisture at the exit from 14 to 4 percent by use of superheated vapor increases the radiator area by a factor of 1.5. Therefore, it appears desirable to use saturated or nearly saturated vapor at the turbine inlet.

The requirements on the turbine of high temperature, high efficiency, and wet-vapor operation impose many severe turbine design problems if good performance and high reliability are to be achieved.

A major factor affecting system reliability is the choice of proper materials of construction. Long-time strength properties are required for the refractory metals considered as containment material. In addition, if different materials are used in the rotating machinery system (shaft, bearings, rotors), a bimetallic condition will exist that could result in severe mass-transfer problems. Since little or no information exists on material long-time strength, corrosion resistance, and fabricability, many problems remain to be solved.

There are additional problems. For example, as the temperature and life requirements increase, allowable design stress decreases. Consequently, turbine-blade speeds must be reduced below present limits. This speed reduction results in an increase in the number of turbine stages required to produce high efficiencies. Although the associated increase in turbine weight may not significantly affect gross system weight, such factors as bearing alignment, clearance allowance for thermal expansion, and moisture-removal techniques become more complex. Figure 46-28 illustrates the moisture formation within the turbine if the condensate is not removed as it forms. As noted, approximately 14 percent liquid, by weight, may be present in the turbine exhaust. The turbine blade material must be able to resist the erosion

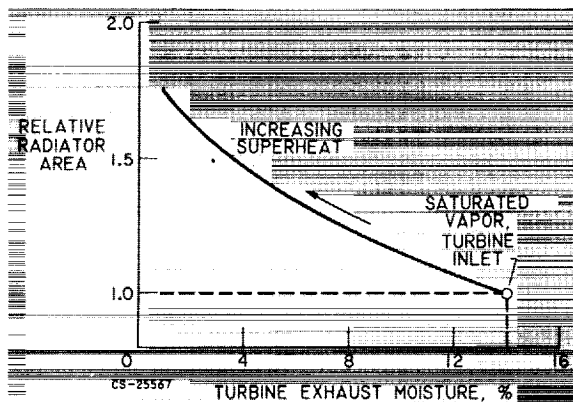


FIGURE 46-27.—Effect of superheat on radiator area.

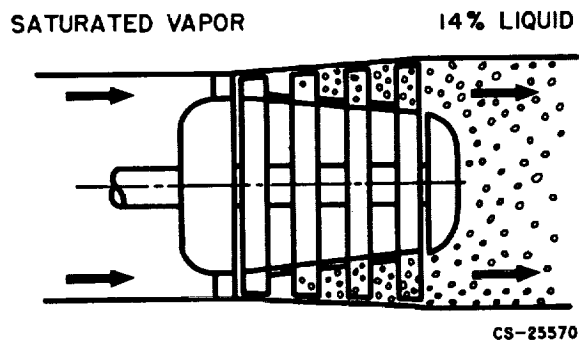


FIGURE 46-28.—Moisture formation within turbine with no moisture removal.

damage that can be caused by the impinging liquid droplets. Condensation, in addition to affecting turbine life by erosion, also causes reduced turbine performance. The performance loss has been estimated at 1 to 1.5 percent for each 1 percent of liquid present.

The state of technology for alkali-metal-vapor turbines may be summarized as follows:

- (1) There are no performance data available for vapor turbines, nor are there any data on moisture damage or its effect on performance.
- (2) There is very limited experience on two-phase flow of the alkali metals in the engineering-size facilities required for component investigations.
- (3) The vapor-property data required for the turbine-design phase are extremely limited.

The present research programs include two experimental vapor turbines operating at intermediate temperatures (1600° F), one to be tested at Lewis and the other by the General Electric Company. These studies will cover areas such as turbine design and performance, moisture formation and removal, moisture erosion damage, and turbine-life characteristics. A research study is also being conducted by the Atomic Energy Commission on the effects of alkali-metal erosion on materials.

**Pumps.**—The functions performed by pumps in closed-loop systems include the circulation of high-temperature liquids and the raising of pressure to the level required by other components in the system. In the vapor loop of the system, the working fluid experiences a change

of phase, and a condensate pump must be used that is capable of pumping the alkali metal at or near boiling conditions. Under these conditions, the liquid will form vapor bubbles (or cavitate) in the pump impeller passages when its pressure is reduced below the vapor pressure corresponding to the inlet temperature. This formation and collapsing of the vapor bubbles can result in severe cavitation damage to the pump parts. The combination of pump cavitation damage and liquid-metal corrosion imposes a severe design problem for condensate pumps requiring long life reliability.

The cavitation problem can be alleviated by moving the condensate away from its boiling point before the pump impeller inlet. One of two methods, or a combination of these methods, may be used. First, the condensate can be subcooled below its boiling temperature by the addition of heat-transfer area in the radiator. Figure 46-29 shows the effect of subcooling on additional radiator-area requirements. Approximately 200° to 300° R of subcooling is required to substantially remove the condensate away from boiling for the alkali metals of interest. Required radiator size must, then, be increased about 8 percent. The second method of moving the condensate away from its boiling point is to prepressurize the liquid above the vapor pressure corresponding to the inlet temperature. Figure 46-30 shows a schematic diagram of a typical inducer used for such a purpose. The inducer is designed to gently raise the pressure of the incoming liquid above vapor pressure before entering the impeller passages. This type of pump has potential, but its effectiveness in liquid-metal pumps has yet to be determined. Another method of prepressurizing the liquid is presented in figure 46-31, which shows a combination jet centrifugal pump used to boost the inlet pressure by a mo-

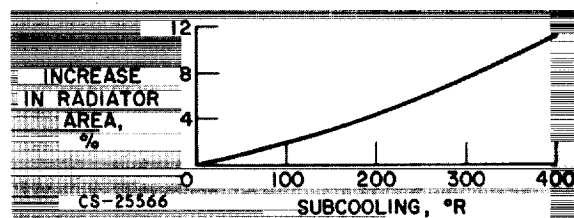


FIGURE 46-29.—Effect of subcooling on radiator area.

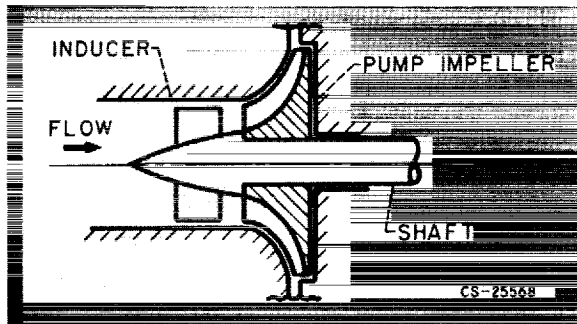


FIGURE 46-30.—Typical inducer for prepressurizing liquid.

momentum exchange with high-pressure liquid from the centrifugal-pump discharge. Approximately half of the flow through the centrifugal pump is recirculated through the jet pump. Even with this device, some radiator subcooling will be required to prevent cavitation in the jet pump.

The state of technology for alkali-metal condensate pumps is as follows:

(1) Experience has been primarily for single-phase-flow circulating pumps operating at intermediate temperatures (1500° F).

(2) Only very limited performance data exist for condensate pumps operating under cavitating conditions with alkali metals.

(3) There is no information on the interaction of cavitation damage and alkali-metal corrosion.

(4) No accurate method exists for predicting cavitation damage rate, even for simple fluids such as water.

Figure 46-32 shows an example of one of the many projects under way to investigate cavitation in condensate pumps. This particular test

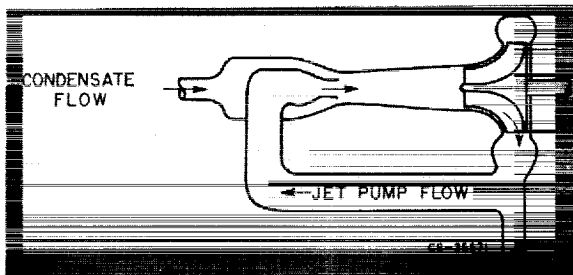


FIGURE 46-31.—Typical jet centrifugal pump for prepressurizing liquid.

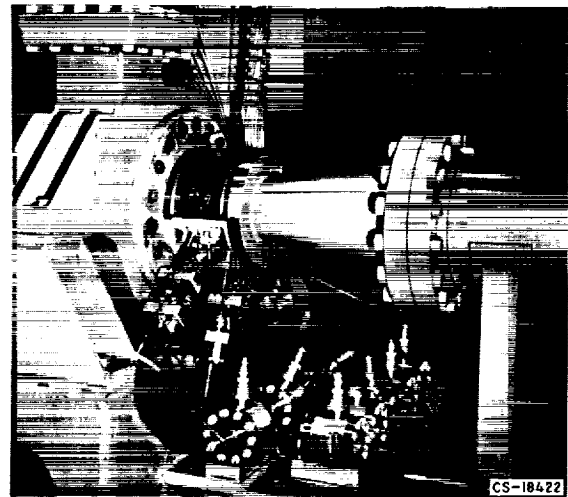


FIGURE 46-32.—Pump inducer operated in Lewis water tunnel.

rig uses water as the test fluid. A transparent casing is used in conjunction with a synchronous light source and camera to study cavitation as affected by operating conditions.

#### MATERIALS FOR RANKINE CYCLE SYSTEMS

CHARLES A. BARRETT. The three principal materials problem areas for nuclear Rankine systems are the reactor, the boiler, and the radiator. In the low-temperature systems (typified by Snap-2 and Snap-8), the reactor and the radiator do not appear to be a major problem. In this system, the mercury boiler presents the problem. A boiler alloy must combine suitable strength, weldability, and fabricability along with good corrosion resistance to boiling mercury on the inside and sodium-potassium from the reactor on the outside. The problem of corrosion is not only the eating away of the wall in the boiler but also the carryover of corrosion products to small passages downstream in the system, such as bearing passages. Figure 46-33 indicates the possible magnitude of this problem. The figure shows boiling reflux corrosion capsules, which were machined from three conventional alloys that were of interest as a Snap-8 boiler material. Figure 46-33(c) is the high-strength, highly alloyed, ductile, cobalt superalloy HS-25. In the center is

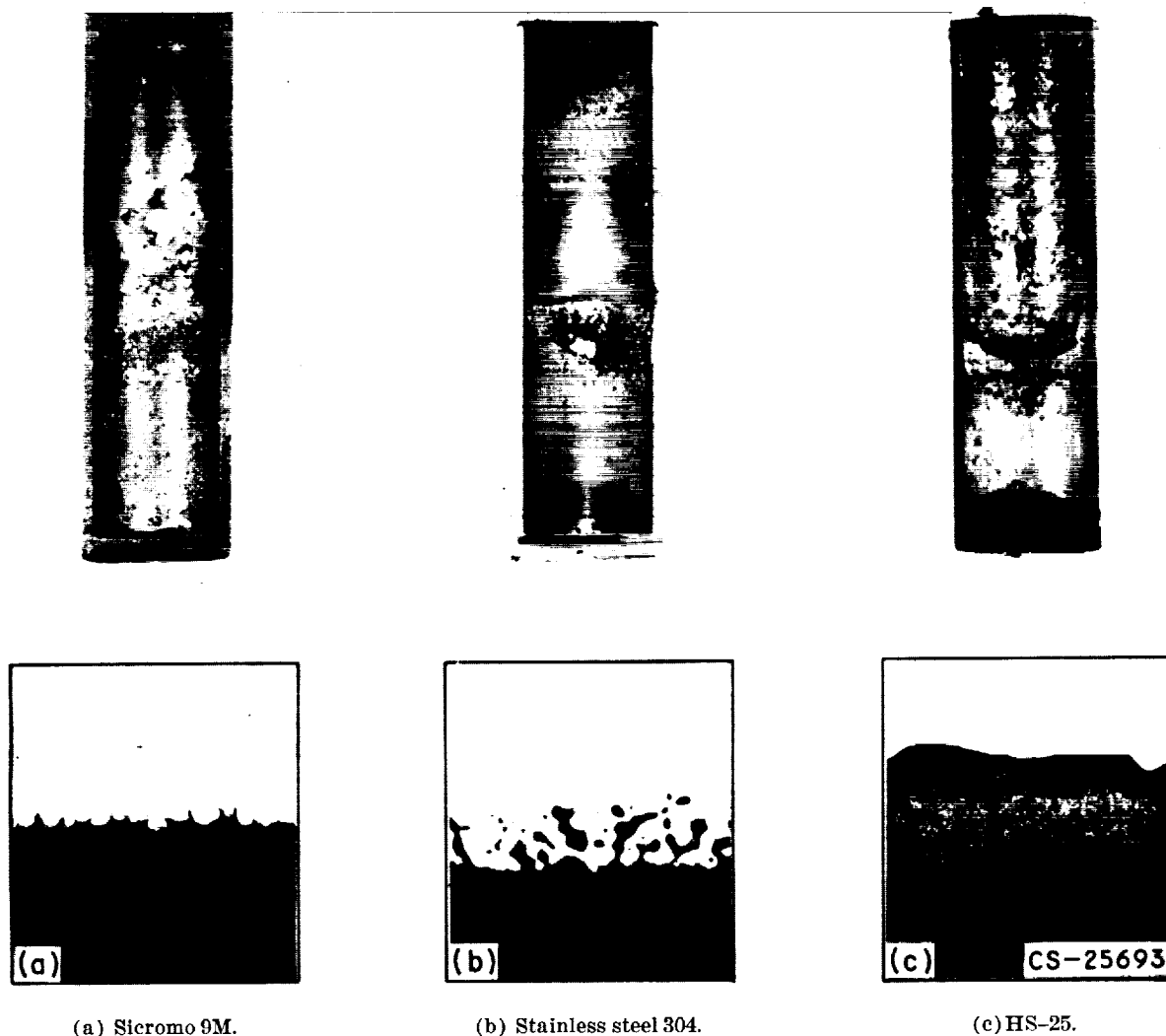


FIGURE 46-33.—Mercury compatibility capsules after 1000 hours at 1200° F.

the conventional austenitic stainless steel 304. In figure 46-33(a) is the high-chromium martensitic boiler alloy Sicromo 9M. These capsules are approximately 2 inches long and 1/2 inch in diameter with a 40-mil wall. The capsules were etched on the inside and then filled approximately one-third full with high-purity mercury. They were then evacuated and sealed under high vacuum by an electron beam welder. The capsules were then placed in small furnaces and heated for 1000 hours at 1200° F. There is a slight gradient of 20° to 40° F between the boiling interface and the tops of the capsule. The liquid region quickly becomes saturated with the more soluble elements such as nickel and chromium. The vapor condenses on the

cooler top part of the capsule and runs down the wall. This virgin liquid continuously leaches out the more soluble elements and builds up a deposit at the boiling interface. This buildup is greatest in the heavily alloyed HS-25, less so in the 304, and very low in the 9M.

The photomicrographs below each capsule in figure 46-33 are cross sections in the heavily leached condensing areas at an original magnification of 250 diameters. The white portion is the unetched metal and its lower edge is the mercury-metal interface. The porous area in the HS-25 photomicrograph is the heavily leached area. The 304 stainless steel shows more of a grain-boundary-type leaching, while the 9M is much less attacked. The 9M still would

generate some buildup, and its creep strength is too low to be used in the boiler.

Although these capsule studies cannot truly simulate the corrosion conditions in an actual boiler, they do indicate that these and similar alloys are quite corrosion prone with mercury.

It was hoped that conventional alloys such as these general-type steels or superalloys could be used as boiler-tube alloys in such systems. The experimental indications, however, are that too large an amount of corrosion products is generated. The present approach, therefore, is to use refractory-metal-lined boilers (such as columbium or tantalum), which by their very nature are virtually insoluble in mercury and generate no corrosion products. This refractory alloy must be clad with stainless steel, however, for suitable strength and compatibility with the reactor materials and fluid. The major problems in this clad-boiler concept are the making of reliably bonded, clad, stainless steel—refractory-metal tubing and the ease and reliability of welding such tubing.

In the advanced system with reactor operating temperatures close to 2200° F and boiler temperatures close to 2000° F, the reactor, the boiler, and the radiator all present formidable problems. In such systems the reactor will set the upper limit. At the present state of the art, a reactor-fluid outlet temperature of 2000° F to the boiler seems reasonable.

For these very high temperatures, none of the conventional stainless steels or nickel- or cobalt-base alloys are satisfactory. An upper-limit temperature of 1500° F is set not by low strength or excessive corrosion but rather by excessive vaporization in the vacuum of space.

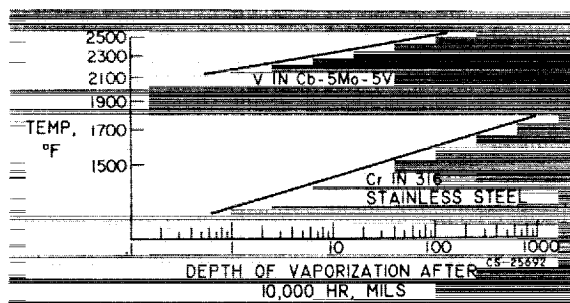


FIGURE 46-34.—Calculated depth of vaporization depletion for typical high-temperature alloys in space. Ideal solution and nondiffusion control assumed.

This effect is shown in figure 46-34. Virtually all the conventional high-temperature alloys contain chromium for oxidation resistance in air. In vacuum, however, chromium has an extremely high vapor pressure, above 1500° F. In an alloy, it would tend to diffuse to the surface and evaporate (or boil away) provided that it was not combined somehow—perhaps as a carbide. Even if chromium could be eliminated, the evaporation temperature of iron and nickel at 1800° F is close to that of chromium at 1500° F, and this proximity would tend to place a temperature limit here. The lower theoretical curve in figure 46-34 is typical for any chromium-containing alloy and shows that for 10,000 hours at 1500° F, 100 mils of chromium would be depleted; this amount is greater than any contemplated boiler-wall thickness.

The advantage of using the refractory metal columbium is also shown on figure 46-34. One of the advantages of the refractory metals<sup>1</sup> is their very low vapor pressures at 2000° F. As long as columbium, for example, is alloyed with other refractory metals or metals such as zirconium, hafnium, or vanadium, evaporation is not a problem. The curve in the figure shows that vanadium in a columbium alloy (again assuming ideal solution and nondiffusion control) would not give 100 mils depletion in 10,000 hours until a temperature of 2500° F was considered. For this reason, as well as strength and corrosion considerations, the refractory metals and their alloys are necessary in the reactor and the boiler. For overall system compatibility, the same metals may have to be used in the radiator also, even though its use temperature may be as low as 1300° F.

Fortunately, the old Aircraft Nuclear Propulsion Program (ANP) developed a suitable high-temperature, compact liquid-metal reactor using the refractory metal columbium. The reliability of such a reactor for the long 10,000-hour life along with adequate corrosion resistance must be proven.

The advanced boiler presents a formidable problem. It involves literally thousands of feet of high-quality, small-diameter, thin-

<sup>1</sup> Refractory metals may be arbitrarily defined as the transition metals columbium, tantalum, molybdenum, tungsten, and rhenium with melting points over 4000° F, exclusive of the platinum group metals.

walled tubing that must be butt welded in suitable locations to make numerous helices and then attached to a header with many high-reliability welds. The alloy to be used is still in doubt. Presumably columbium—1-percent-zirconium alloy will be used as tubing because a great deal of fabrication and corrosion experience was obtained with it during the ANP program. There is some question of whether it has the long-time creep strength and corrosion resistance needed for space power systems. There may be an embrittlement problem on welding also. Other refractory-metal alloys based on columbium and tantalum are currently being developed which, supposedly, have better overall tubing properties than columbium—1-percent-zirconium alloys. These alloys must still be further evaluated.

A major problem with columbium and tantalum alloys (as with all refractory metal alloys) is not only that they oxidize catastrophically at elevated temperatures, so that they cannot be tested in air unless coated or clad, but also that they dissolve large quantities of gases like oxygen when exposed at high temperatures. They are "getters" and essentially act as pumps to pick up these gases. These gases change the properties of the alloys drastically, change their fabricability, weldability, creep strength, and resistance to alkali-metal corrosion. The main problem in testing these alloys is to provide conditions under which their properties are not being altered by their test environment. This probably means testing in ultrahigh vacuums, which is not only expensive but, because so few test facilities are available, gives rise to long delays in securing design data. In addition, the turbine problem exists for which long-time detailed corrosion, erosion, and especially creep-rupture data must be obtained.

Strength curves for refractory metal alloys are shown in figure 46-35. The lower curve is for the columbium tubing alloy columbium—1 zirconium and is shown in comparison with the cobalt-base alloy HS-25. Most of the advanced tubing alloys fall between the columbium-1-zirconium and the tantalum-10-tungsten alloys. It shows that the hoop stress gen-

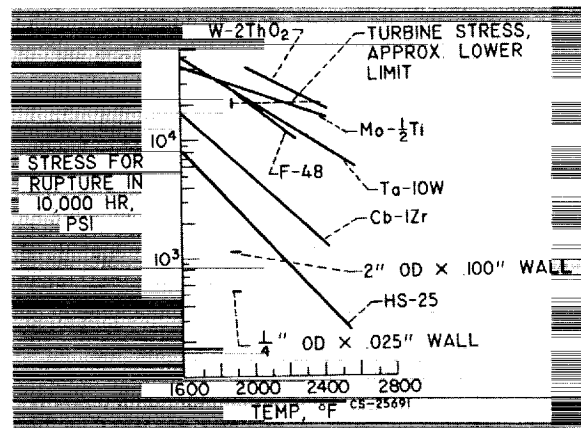


FIGURE 46-35.—Strength requirements for advanced space power systems. Turbine hoop stress at temperature of 1900° F. for potassium.

erated in the boiler at 1900° F by potassium should not cause rupture of two possible sizes of boiler tubing in 10,000 hours. These curves are extrapolated from short-time data (from 100 to 300 hr) and from higher level stress data. The data must be verified for long times and low stresses before they can be used in an actual system.

More important than rupture data are low-stress creep data, which must be obtained for tubing alloys before they can be used.

The dashed line at 20,000 psi represents a turbine stress, and here a whole new class of very-high-strength refractory metals are needed. Fortunately, high-strength tungsten and molybdenum alloys can also be considered. These alloys, because of their limited ductility and fabricability, as yet have not been considered for tubing. Here, also, long-time rupture and creep data are very meager.

Even the existing data for columbium and tantalum alloys are questionable, for it is not known how the environment affected the results. Obviously, a detailed testing program is needed, not only in ultrahigh vacuum but eventually in the alkali-metal environment.

Compounding the problem of contaminating the refractory alloy is that of contaminating the alkali metal, which must be purified, analyzed, and transferred all under high vacuum wherever possible to minimize the pickup of deleterious gases.

In summary, in the advanced systems an entire new technology exists that involves alkali metals and refractory metals where a contamination-free environment is an absolute must. For the alkali metals, such as potassium, rubidium, and cesium, there is little purification, analyzing, and handling experience. High-reliability tubing using tantalum- and columbium-base alloys is still in an early state of development. It will also be necessary to run complicated corrosion and component test loops, which as yet have not been run successfully, even at lower temperatures under easier test conditions. Obviously, a great deal of research is needed before such a system can be seriously considered.

Additional materials problems exist in the pump and alternator, along with bearing problems in the various rotating components.

Finally, the radiator presents, for the advanced system, the third major problem area. Here must be fabricated literally thousands of feet of refractory-metal-alloy tubing (columbium or perhaps vanadium base) over which is clad a bumper-finned material of pyrolytic graphite or beryllium, both extremely brittle and difficult to fabricate and of uncertain compatibility with columbium or vanadium. Producing a reliable radiator of several thousand square feet of this combination of material, with the numerous brazed or welded joints having the required reliability, is extremely difficult. For this reason, the radiator appears to be the most severe problem in the advanced system, at least from a materials standpoint.

### THERMIONIC CONVERTERS

A. E. POTTER, JR. As stated previously, another technique for converting reactor thermal energy to electric power involves the use of thermionic converters. The essential features of a thermionic converter are shown in figure 46-36. It consists of a high-temperature electron-emitting surface (the cathode) and a lower-temperature electron-collecting surface (the anode). The number of electrons boiling off the hot emitter is greater than the number from the cooler collector, so that a charge builds up on the collector. This charge or voltage can

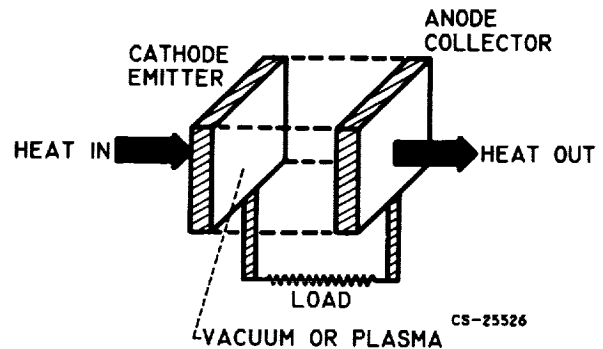


FIGURE 46-36.—Thermionic converter.

be used to drive current through an external load.

The thermionic converter has several attractive features for space power. It can be quite efficient, converting up to 17 percent of heat to electricity. It is small and compact. It operates at high temperatures, 2000° to 3000° F. High operating temperatures for heat engines working in space are a great advantage, since high temperatures mean small and lightweight radiators.

Although the principle of the device is old—Edison held the first patent on a thermionic generator—it is only recently that practical converters have been made, and the device is not yet completely perfected. The bulk of the research on thermionic converters has been aimed at improving efficiency. The principal route to improvement of efficiency has been to reduce space charge between the electrodes. Space charge limits current flow between the electrodes. Two good methods of reducing space charge have emerged. One is to reduce spacing between the electrodes to less than 0.004 inch. This reduces space charge, but makes the device difficult to fabricate in large sizes. Another way of reducing space charge is to introduce cesium vapor between the electrodes. This procedure seems to be the most useful method yet devised, although research is continuing to find still other ways of reducing space charge. Another route to improved efficiency is to reduce heat losses by conduction through the sealing material and radiation losses across the electrode gap. Choice of electrode materials having the proper work functions is also important in achieving highest efficiencies. When

properly used, cesium vapor plays a dual role, not only suppressing space charge, but also adjusting the work function of the collector to a suitably low value by means of partial absorption of cesium on the collector surface.

The remainder of research in thermionics can be classified as research on the lifetime of the device. Some of the problems are the following. Evaporation of electrode material from the emitter and its subsequent deposition on the collector can eventually build up needlelike deposits, which can short out the device. If cesium is used to suppress space charge and control work function, it corrodes the sealing materials and may eventually cause a leak. If no cesium is used and close-spaced electrodes are employed to suppress space charge, creep and flow of the electrodes will eventually alter the spacing from its optimum value. The general problem of maintaining the device in operation for 10,000 to 20,000 hours at 2000° to 3000° F is a difficult problem. Progress is slow, although some 3000° F converters have been operated for 1000 hours.

When the practical difficulties associated with the use of the thermionic converter are overcome, it seems likely that its major use in space will be in conjunction with a very-high-temperature nuclear reactor to provide power in the megawatt range.

#### THERMIONIC-REACTOR POWER SYSTEM

DANIEL T. BERNATOWICZ. Several ways exist in which thermionic converters can be incorporated into a system, but the most promising way is to put the converters into the reactor core, integral with the fuel elements. Figure 46-37 is a schematic diagram of a thermionic reactor system. Cylindrical thermionic converters are connected in series and are stacked inside tubes. The central region of each converter is filled with nuclear fuel. The surface of the fuel can is the emitting surface. Coaxial with the emitter is the collector, and the space between the electrodes is filled with low-pressure cesium vapor. Between the wall of the containment tube and the collector is a layer of electrically insulating material to prevent short circuiting of the converters. Heat generated in the nuclear fuel maintains the emitter

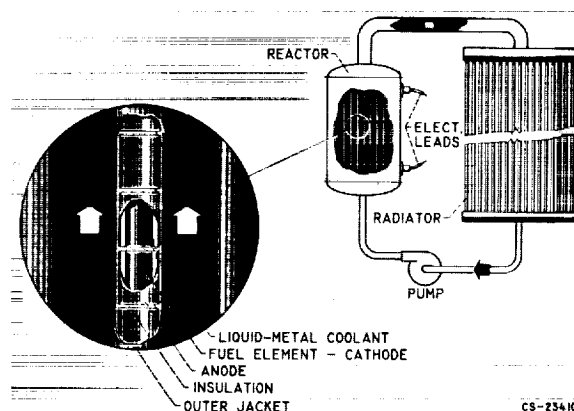


FIGURE 46-37.—Thermionic-reactor power system.

at a high temperature. The collector is cooled by conduction through the insulator and the tube wall. The tube wall is cooled by a liquid metal, which probably will be lithium.

Several hundred of these tubular thermionic fuel elements are assembled into a reactor core. Liquid-metal coolant is pumped through the core assembly and the heat is rejected in a radiator.

Because only the fuel and the emitter operate at the maximum temperature, it is reasonable to expect that this system can operate at higher temperatures than the Rankine cycle system, in which the liquid metal and the turbine are exposed to the maximum temperature. Also, the small number of moving parts in the thermionic system suggests high reliability. If an electromagnetic pump, which is composed only of static elements, is used, moving parts are needed only in auxiliary equipment, such as the reactor control system.

Studies of the thermionic systems as well as the Rankine cycle system are based on information inadequate to justify a selection of one system over the other at this time. Weight estimates, however, indicate that the thermionic system may be lighter than the Rankine cycle system.

Although the potential for the thermionic system is high, difficult problem areas and serious deficiencies in knowledge and technology are recognized. The very feature that makes the thermionic reactor system appear so attractive, that is, that the heat source and the energy conversion device are closely integrated, com-

pounds the engineering problems. Information on nuclear fuels, seal and insulator materials, and fabricating techniques is not sufficient to assure that the converters can operate reliably for years at high temperature under the intense radiation in the reactor core. Also, little work has been done on systems of converters. Several thousand converters will be connected in a series-parallel network in the system described here. Because of reactor heat-generation characteristics, there will be a variation in temperature among the converters. How seriously this variation will affect the performance of the system as a whole has not been established. There may also be electric oscillations or large stray currents in such a large network. Furthermore, thermionic converters are low-voltage d-c devices. Power conditioning equipment will be needed to raise the voltage to the several thousand volts d-c required by the electric propulsors. The weight of this equipment may be a substantial part of the total weight. Nevertheless, the high performance that may be possible for the thermionic reactor system certainly justifies undertaking the solution of these many problems.

#### CONCLUDING REMARKS

NEWELL D. SANDERS. The long durations of space missions place severe requirements upon space power systems. Trips to the planets will take 1 or 2 years or perhaps more. Elaborate satellites such as those being planned

for communication, weather observation, and space stations are expensive to build and launch. A long life, at least a year, is a requirement with respect to economy and practical operation.

This requirement of a long life without attention has a profound effect upon the course of development. Many paths may be pursued in the initial laboratory and bench investigations of components and breadboard systems. A tremendous gap exists, however, between the bench proof of performance and the actual achievement of a flyable power system with the desired lifetime. The development cost involved in crossing the gap is measured in tens of millions of dollars for even the simplest systems. In the case of the very large multimewatt systems, the development cost will be hundreds of millions.

Because of the great cost and the drain on technical manpower, unwise choices of systems for development will impede seriously the space program. Technical information is absolutely necessary for making these decisions. The technical information must be provided by a broad-based program of research and preliminary development in critical areas.

In the light of the foregoing discussion and because of the many unsolved technological problems that were discussed in earlier portions of the paper, it is concluded that a healthy program of supporting research is absolutely necessary to a successful program of space power development.